Development of a Mars Wind Tunnel and Its Applications to Low Reynolds Number and High-subsonic Airfoil Testing

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論文内容要旨

An idea of Mars exploration by aircraft has been considered as a new and attractive approach to obtain scientifically interesting data about the Martian surface and atmosphere. The aircraft can get higher resolution data than orbiting satellites and can provide larger spatial coverage than ground rovers. Several options for Mars aircraft have been proposed by many researchers. In view of these advantages and disadvantages, it is considered that the airplane with a fixed wing is the most promising approach for Mars aerial exploration. This approach, however, is facing challenging propositions in engineering viewpoint. The main feature of Martian atmosphere is that the density and the temperature are lower than those of Earth and also the main atmospheric constituent is CO_2. This means that a Mars airplane is required to fly in low Reynolds number ($Re = 10^4$-10^5) and high subsonic Mach number conditions. The design criteria for conventional Earth airplanes cannot be directly applied to the design of Mars airplanes because the flight condition in Martian atmosphere is very different from that in the earth atmosphere. To determine the optimal shape of a Mars airplane, it is important to precisely predict its aerodynamic performance in low Reynolds number and high subsonic Mach number flow, but the experimental airfoil data corresponding to the flight conditions of the Mars airplane is lacking. Numerical studies for the optimum design of a Mars airplane have been also made. However, these computational results may not have satisfactory accuracy for simulating the flow field on an airfoil of the Mars airplane because the flow field will become highly complicated with a strong interaction of viscous effect and compressibility effect in low Reynolds and high subsonic flow. To simulate the actual flight condition on Mars in wind-tunnel experiments, it is necessary to conduct airfoil tests on the basis of the similarity rule for Reynolds number, Mach number and the specific heat ratio. To achieve similarity between the actual flow in the Martian atmospheric flight condition and a flow in a wind tunnel, it is required to use a low density wind tunnel that can simulate flight condition on Mars. However, there is no wind tunnel that is suitable for evaluation of the airfoil performance of Mars airplanes. In order to study the similarity rule for the

low Reynolds number and high subsonic airfoil flow, it is required to construct a new wind tunnel specifically designed for this purpose.

Therefore, our research was conducted for the following two purposes. One is to develop a low density wind tunnel that has a capability to conduct airfoil tests in low Reynolds number and high subsonic flow. The other one is to investigate aerodynamic characteristics and to study the similarity rule in a Martian atmospheric flight condition.

First, as a new type of low density wind tunnel, "The Mars Wind Tunnel (MWT)" has been developed. The MWT was designed and constructed at Tohoku University in late 2007 for evaluating airfoil performance in low Reynolds number and high subsonic flow. The shakedown tests started in early 2008. In these tests, initial operational performance was investigated, but the detailed operational performance including flow qualities were unknown. Furthermore, this tunnel was driven only by air in the original design and could not be operated by CO_2. To satisfy the similarity rule for Reynolds number, Mach number and the specific heat ratio, the operation system was firstly modified to allow for operation in CO_2 mode by installing a CO_2 supply system to the MWT. A great amount of CO_2 is required to drive the MWT. Hence, for efficient operation, the CO_2 supply system was designed to use a liquid CO_2 as a gas source. After this modification, the operational envelope and the flow quality in the test section were evaluated by comparing the results in air and CO_2. Use of CO_2 allows the tunnel to be operated at higher Mach numbers, because the molecular weight of CO_2 is larger than that of air. The achieved Reynolds number range is from 2.6×10^3 to 1.1×10^5 with the Mach number range up to 0.74 in air. On the other hand, the Reynolds number range is from 4.2×10^3 to 1.3×10^5 with the Mach number range up to 0.84 in CO_2 mode. In the design stage of the CO_2 supply system, there was a concern for CO_2 solidification at the outlet of the ejector nozzle. In actual condition, however, no noticeable effect of CO_2 solidification on the tunnel performance and operation was found, probably due to heat addition from the mass of the gas supply line and the ejector and mixing with the surrounding gas. To clarify the effect of boundary layer on the test section, the flow distribution and the static pressure gradient were measured. The flow velocity in the test section is considerably uniform in all cases. The velocity deficit caused by the boundary layers near the walls is larger in air mode than in CO_2 mode. The results of static-pressure gradient measurement in the test section show that the effects of boundary-layer development along the test section can be controlled by adjusting the inclination angle of the both upper and lower walls. The residual effects are small but, it was found that, when a drag measurement to one-count accuracy is required, the inclination angle must be readjusted depending on the total pressure of the flow. The results of these experiments show that the Mars Wind Tunnel can simulate the real flow condition of cruising flight of Mars airplanes. It should be emphasized also that the MWT allows us to evaluate individual effects of Reynolds number, Mach number and the specific heat ratio on airfoil performance on airfoil performance for Mars airplanes.

The MWT employs the ejector driving system to induce the high subsonic flow in low pressure condition. There are few examples in that ejectors are used as a driver of the low density wind tunnel. The driving performance of the ejector under low density condition has not been well understood and the evaluation method has not been established yet. For optimum design of the ejector driver of the wind tunnel, it is necessary to derive an analytical evaluation methodology that can predict the Mach number in the test section from a configuration of the ejector system and an operational condition. A new method to evaluate performance of supersonic ejectors under low pressure condition has been proposed. In this method, the ejector drive parameter (EDP) that is based on the previous studies on supersonic ejectors at one atmosphere is adopted as the correlation parameter. The results of experiments using a model ejector at low pressure condition have indicated that the pressure ratio can be correlated with EDP very well even when ambient pressure, ejector configuration, operational condition and a combination of test gas species are changed extensively. Furthermore, it was found that all experimental results were in excellent agreement with the one dimensional analysis. It can be said that EDP is an effective parameter to predict the pressure ratio of supersonic ejectors over the wide range of pressure. The results of model ejector tests were applied also to evaluate ejector driving performance of the MWT. It was found that the pressure ratio of the MWT in air and CO_2 operation modes can be expressed as a common function of EDP. The experimental results in the MWT agree well with the one dimensional analysis. The results of the MWT tests and the model ejector tests can be fitted with a common function of EDP, meaning that EDP is a universal parameter for predicting the pressure ratio of supersonic ejectors. The present methodology using EDP can be used to predict the Mach number in the test section from the pressure ratio. The guidelines for improving the MWT's ejector design have been developed, particularly for future experiments under low temperature.

Finally, to evaluate the aerodynamic characteristic of airfoils in low Reynolds number and high subsonic flow, airfoil tests were conducted in the MWT. Test models were a 5%-thick flat-plate and an NACA0012-34 airfoil. A two-component balance system and Pressure-Sensitive Paint (PSP) technique have been developed for the MWT tests. Both the balance system and PSP technique have proved to be an effective tool to measure lift and drag forces and pressure profiles on airfoil models in the MWT. Using PSP, pressure distributions caused by laminar separation bubble were clearly visualized. For the flat plate, Reynolds number affects both the lift slope and the drag characteristics of the flat plate, while Mach number effect does not have much effect on the aerodynamic performance. PSP measurements show that the observed change in the aerodynamic characteristics is closely related to the behaviors of leading-edge separation bubbles. The separation bubble behaves moderately and its length increases gradually with increasing angle of attack. The separation bubble length is strongly dependent on Reynolds number at the zero angle of attack. It was found that this phenomenon is caused by a change of the reattachment mode of the separated shear layer with Reynolds number. The separated shear layer reattaches on the model surface in laminar state for $Re < 6.1 \times 10^3$. On the other hand, the reattachment occurs in turbulent state for $Re > 1.1 \times 10^4$. For NACA0012-34 airfoil, both Reynolds and Mach number effects become more prominent compared with the flat plate model. The lift curves are highly nonlinear and the drag polars show a complicated variation that is affected by the behaviors of laminar separation bubbles in trans-critical conditions. The lift rapidly increases at the angle of attack where the separated shear layer reattaches on the model surface. At the lowest Reynolds number of 4.1×10^3, the reattachment does not occur until a high angle of attack. A comparison of the results obtained at different Mach numbers has suggested that the compressibility has an effect of stabilizing the shear layer and delaying separation and transition to turbulence. The specific heat ratio was also found to affect the aerodynamic performance. This result is unexpected by the theory. In CO_2 case, a stall occurs faster compared to the case in air. In addition, at low Mach numbers, the drag in CO_2 becomes smaller than that for air. On the other hand, the difference of drag polar in air and CO_2 is small in high subsonic flow. At this moment, PSP capable of measuring the pressure distribution on model surface in CO_2 is not available. It is also suggested in the current work that unsteady phenomena such as vortex shedding occurs at large angels of attack. In response to these, further development of PSP technique and unsteady measurements will be required.

論文審査結果の要旨

火星表面や大気成分の科学的な調査を行う手段として航空機を用いる方法が注目されている。本研究は，地球とはその成分や熱力学的状態がまったく異なる火星大気を飛行する航空機の翼を設計するための「火星大気風洞」の開発と翼型実験への適用について論じたもので，実験手段としての火星大気風洞の有効性を系統的に評価し実証するとともに，火星大気飛行における２つの翼型の空力特性と流体現象の関係を相似則の立場から論じている。本論文はこれらの研究成果をまとめたものであり，全編５章からなる。

第１章は緒論であり，本研究の背景，目的および構成を述べている。

第２章では，火星大気風洞による火星飛行条件の模擬可能範囲と模擬精度が論じられている。まず，同風洞を火星大気の主成分である二酸化炭素（CO_2）で駆動するための装置改修について述べ，圧力が大気圧から大気圧の 100 分の 1 の範囲内で，作動気体が空気と CO_2 の場合の運転可能範囲を調べている。その結果，空気の場合は，翼弦長基準のレイノルズ数（*Re* 数）が $2.6\text{x}10^3$ から $1.1\text{x}10^5$ まででマッハ数（*M* 数）が 0.74 までの範囲，CO_2 の場合は，*Re* 数が $4.2\text{x}10^3$ から $1.3\text{x}10^5$ までで，*M* 数が 0.84 の範囲が模擬できることを示している。合わせて，測定部気流の系統的な検定試験を実施し，上記の範囲内では速度分布が一様であること，また，流れ方向の速度勾配が上下壁の傾き角で補正できることを明らかにしている。これは，火星飛行機の空力設計を高度化するための実験技術上の極めて重要な成果である。

第３章では，火星大気風洞の駆動に用いられている超音速エジェクタの低圧における性能評価法について述べている。単一ノズルからなる模型エジェクタに対して，周囲圧力，ノズル形状，駆動圧，作動気体を広範囲に変化させた系統的な実験を低圧環境下で行い，取得した全てのデータが “Ejector Drive Parameter” (EDP)と呼ばれる相似パラメータで整理できることを示している。また，これらの結果を火星大気風洞のエジェクタの性能推定に適用し，EDP が形式の異なるエジェクタに広く適用可能な相関パラメータであることを明らかにしている。これは，超音速エジェクタを設計する際の有力な設計指針となるだけでなく，将来火星大気風洞のさらなる機能向上の可能性を示す重要な成果である。

第４章では，*Re* 数と *M* 数を独立にかつ広範囲に可変できる火星大気風洞の特徴を利用して，5%厚さの平板翼と NACA0012-34 翼型の空力特性に対する粘性の影響と圧縮性の影響を実験的に調べ，流体現象との関係を論じている。新規開発した空気力天秤と感圧塗料(PSP)を用いた計測により，これらの翼型に作用する揚力と抗力が翼表面に生じる層流剥離泡の挙動に左右されること，また，層流状態で剥離した剪断層の乱流への遷移が圧縮性の効果によって緩和されることなどを明らかにしている。これらの成果は，従来の風洞装置では決して得られなかったものであり，応用面だけでなく学術的にも極めて重要な成果である。

第５章は結論である。

以上要するに本論文は，火星大気飛行を実現するための翼を設計する基盤技術を構築するため，火星での大気飛行状態を模擬できる新しい風洞と計測技術を開発し，それを翼型に対するレイノルズ数やマッハ数の影響の評価に適用することで，火星飛行機の翼の空力設計に関する重要な知見と成果を得たものであり，航空宇宙工学および実験空気力学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。